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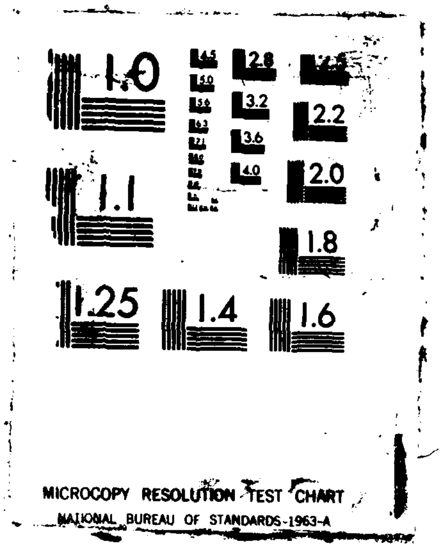
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WESTERN INSTRUMENT CORPORATION

FINAL REPORT

CABLE AND CABLE DYNAMICS ANALYSIS OF CSSSRNM ARRAY INSTALLATION NANAKULI, HAWAII

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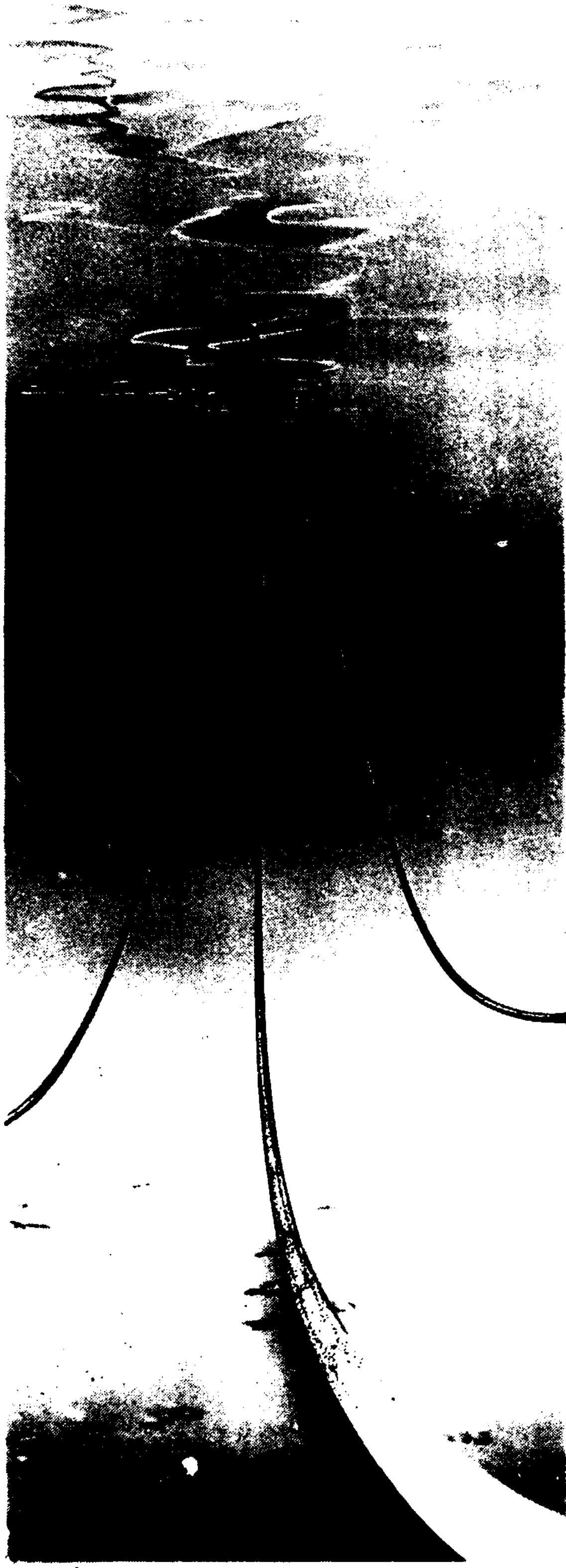

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WESTERN INSTRUMENT CORPORATION
OFFSHORE ENGINEERING

PREPARED FOR:

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WASHINGTON, D. C. 20374-2121

APRIL 1987

FINAL REPORT

CABLE AND CABLE DYNAMICS ANALYSIS OF CSSSRNM ARRAY INSTALLATION NANAKULI, HAWAII

87 6 30 230

4050 MARKET STREET VENTURA CA 93003 TEL: 805-644-1051 TELEX: 469023 TELEFAX: 1-805-644-0724

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This report analyzes the CSSSRNM cable design and provides a dynamic stimulation analysis of the proposed cable installation. It also makes recommendations concerning the installation plan.

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1.0 INTRODUCTION

The Naval Facilities Engineering Command has contracted with Western Instruments Corporation (WIC) for WIC to provide support for ocean engineering and cable engineering projects. This report discusses the analysis of the cable and cable dynamics of the Combined Surface Ship and Submarine Radiated Noise Measurement (CSSSRNM) Array, to be installed off of Nanakuli, Hawaii.

The statement of work for this project lists three primary tasks. The first task is to determine and confirm the mechanical parameters of the specified cable and and armor package. The maximum tension loading and bend diameters that the cable will withstand without failure is also to be calculated. The task shall also recommend and confirm safe working loads for cable handling.

The second task in the statement of work is to simulate the cable laying operation. A dynamic cable analysis program such as SEADYN, is to be used in the time-domain to determine the maximum loads expected on the cable during installation. The two primary points of interest in this analysis consist of (1) the loading on the Sea Cable as it supports the double armored Shore Cable in the water column, and (2) the installation procedures and configurations to prevent undue loading on the cable during the entire operation.

The third task consists of recommending the maximum tension and ship velocity as a function of time, while laying the cable over the escarpment and on the downslope portion of the cable laying operation.

Additionally, recommendations are to be made concerning any subsequent actions compatible with the findings of the statement of work. Any backup information supporting the recommendations will be provided.

2.0 PHYSICAL AND ENVIRONMENTAL DESCRIPTION OF THE SITE

2.1 Location

The site of the proposed cable laying operation is on the western side of the island of Oahu near the town of Nanakuli (see Figure 1). The actual cable will be deployed on a line approximately southwest from the south tower at Nanakuli, HI, and will extend approximately 3.5 miles seaward.

2.2 Sea Floor Configuration Over Proposed Cable Route

The sea floor configuration along the proposed cable route generally consists of a relatively smooth shelf area, a high, steep escarpment, and another relatively smooth area in the deep water below the escarpment. The sea floor along the proposed route has been a subject of intense interest since November 1982,

when Hurricane Iwa passed through the Hawaiian Islands (reference 1). At that time there were numerous cable breaks and equipment damage due to the effects of the hurricane and the large waves in the area. Specifically, there was much slumping of the escarpment near the edge of Penguin Bank, and other sub-surface activity in the general vicinity of the proposed cable site (reference 2).

A complete profile taken along the proposed cable route (reference 3) is shown in Figure 2. Since the escarpment near the edge of Penguin Bank is the area of much interest, an enlargement of that portion of the sea floor is presented in Figure 3.

The sea floor from the South Tower to the array site can be divided into three regions: Nearshore, Escarpment, and Downslope. The Nearshore region consists of the shelf area shoreward of Penguin Bank, Penguin Bank and its terrace, and the shelf seaward of Penguin Bank to the top of the escarpment. The Escarpment region consists of the escarpment itself and the boulder/sediment zone at the base of the Escarpment. The Downslope region consists of the area seaward of the base of the boulder zone.

These regions are discussed in detail in Reference 3, and a brief summary is given here.

The Nearshore region generally has a gentle slope of approximately 3 to 4 degrees. The sea floor sediments consist of carbonate sand with both carbonate and volcanic rubble. The seaward edge of Penguin Bank is marked by a terrace that consists of a 3- to 15-ft-high, vertical to near-vertical step of carbonate rock.

The escarpment consists of vertical to near-vertical, 3- to 15-ft steps with 30- to 50-degree, 3- to 6-ft-wide ramps connecting the steps. The total vertical relief of the escarpment is approximately 300 ft. The boulder/sediment area at the foot of the escarpment extends a horizontal distance of about 400 ft at an approximate slope of 10 degrees. This area consists of large carbonate blocks, partially buried in sediment.

The Downslope region, seaward of the boulder area, has a seafloor slope of approximately 8 degrees and consists of carbonate ooze/silt or gravely debris-flow deposits.

2.3 Wind and Sea Conditions

The proposed cable site, shown on Figure 1, has similar geographical and environmental conditions to that of Keahole Point, on the Island of Hawaii. Since Keahole Point was a prime candidate for the OTEC cold water experiment, much information has been published regarding geographical and environmental conditions there (reference 4). Both Keahole Point and Nanakuli are located on the western portions of their respective islands and, therefore, have similar environmental inputs. During normal trade wind conditions, the average wind velocity at Nanakuli is 15 kts,

and average Sea State is 3. These would be the environmental conditions expected during normal cable laying at this site.

3.0 PHYSICAL AND MECHANICAL PROPERTIES OF THE CABLE

3.1 Overall Cable

The overall cable is approximately 28,000 ft in length. It is subdivided into three distinct segments. Segment one (Shore Terminus) is identical in construction to the Sea Cable and 600 ft in length. Segment two, the Shore Cable for the shore-zone and escarpment, is the basic Sea Cable construction with an additional armor layer, and is 7,000 ft in length. Segment three (downslope) is Sea Cable and is 20,400 ft in length.

3.2 Shore Terminus and Sea Cable

A cross-sectional view of the cable construction for the Sea Cable, segments one and three, is shown in Figure 4.

3.3 Shore Cable

The Shore Cable construction has as its core the .90-in.-O.D. Sea Cable and is overlain with a second and third armor layer for abrasion protection. The overall diameter of this double-armored section of cable is 2.20 in. The cable specification is presented in Figure 5.

4.0 ANALYSIS OF CABLE DESIGN

4.1 Cable Strain

The total strain on any one element in a cable (Et) is composed of the sum of constructional strain (Ec), bending strain (Eb), and axial strain (Ea); therefore:

$$Et = Ec + Eb + Ea. \qquad \text{EQ. 1}$$

The constructional strain results from bending of the elements into a helix as they are laid into the cable. This portion of the total strain is more important to optic elements than to copper ones, because copper can yield slightly and take a set, but the optic elements could fail under long term strains as low as 0.001 in./in. Long term, in this context, is considered to be more than 6 months. The bending strain occurs when the cable is deployed over a sheave and also, in this case, over the edge of the escarpment. The axial strain is generated by the tension placed on the cable during installation or by a suspension.

4.1.1 Construction and Bending Strain

Both Ec and Eb can be calculated using cylindrical beam analysis. This type of analysis is a worst-case

analysis, because it assumes that the cable is rigid (ignores helix angles), and the elements cannot move within the cable structure. The approximation can be improved by using the element lay angle (A) in the equation as shown in Equation 2.

$$Eb = \frac{r \cos^2 A}{Rs + Rc} \qquad \text{EQ. 2}$$

r = radial distance from cable axis to element
Rs = Radius of sheave
Rc = Pitch dia./2

This approximation still assumes that the elements are not free to move with the cable structure as it bends around the sheave (Rs), but it can be further improved by the selection of a value for Eb based upon practical experience. The maximum amplitude for bending strain can range from 0.3 percent to 2.0 percent, depending upon the material under consideration, the cable construction, and the calculated cable strains that have proven successful in past cables. The value used is selected by the cable designer based upon experience with similar cables. For this cable design, bending strains from 0.4 percent (at the center of the cable) to 1.8 percent (at the outer armor) were used to calculate a minimum bend radii. This calculation can only be used as an indicator of the minimum bend radii to plus or minus 20 percent.

4.1.2 Axial Strain

The axial strain in the cable is calculated using a set of non-linear equations which take into account material data and constructional geometry. This calculation is performed within a cable design program. The axial strain component of the total strain is very small, as can be seen in the loading table presented in Figure 6. This table was generated by the cable design program. The program was run for both the Sea Cable and Shore Cable cases.

4.2 Calculated Minimum-Bend Radii

To determine the minimum-bend radius for the cable, the minimum bending radius for each component is first calculated to find the limiting component. Axial strain is not considered in this calculation. The allowable bend radius for the cable can then be determined from Eq. 2 by substituting Et for Eb and solving for Rs. As stated above (4.1.1) the bend radius is calculated to a tolerance of +/- 20 percent.

4.2.1 Optic Tube

Assuming allowable strain on the tube of 0.004 in./in., a cable diameter of 2.2 in., and a radial axis for the tube of 0.0625 in., the minimum sheave (bend) radius calculated is 14.5 in. The small-bend radius results from the fact that the tube is located on the cables center axis and (r) is very small. The optic elements with the tube will only be subject to a portion of the tube strain, but in the worst case analysis, it is assumed that the fibers experience the same strain as the tube.

4.2.2 Copper Elements

The power conductors and the quads have a pitch diameter of 0.328 in., a lay length of 3.9 in., and a lay angle of 14.8 degrees. Based on an allowable strain of 0.008 in./in., the minimum bend radius calculated is 19 in. Using the same allowable strain, the minimum bend radius for the single conductors (#20 AWG) is 25 in.

4.2.3 Armor

4.2.3.1 Sea Cable

The single-layer of armor wire in the Sea Cable has a pitch diameter of 0.695 in. and a lay angle of 12 degrees. Using an allowable strain of 0.015 in./in., the calculated minimum bend radius is 22 in.

4.2.3.2 Shore Cable

Based on a pitch diameter of 1.509 in. for the outer armor package on the Shore Cable, the calculated minimum bend radius is 38 in. Based on all of the bending radii calculated for the cable this is the controlling radius.

4.3 Recommendations Regarding Cable Handling

The cable design shown in Figures 4 and 5 should perform the designed task without modification as long as the bend radius for the outer armor is kept between 31 and 45 in. The added axial strain due to tension does not increase the bend radius for loads up to approximately 7,500 lb. The required minimum bend radius increases as the cable tension increases but stays within 20 percent of 38 in. at tensions up to 15,000 lb.

5.0 CABLE LAYING SIMULATIONS

5.1 Method of Analysis

The cable laying analysis can be subdivided into three distinct regions: Nearshore, Escarpment, and Downslope. The Nearshore and Escarpment regions have the armored Shore Cable, whereas the Downslope region has the Sea Cable. Note that there is also a 600-ft. segment of Sea Cable at the shore termination of the Nearshore portion of the cable, but it will not be analyzed specifically, since it has been assumed that it will not pass through the surf-zone.

Since a parametric study is required with cable paying out from a ship, the general purpose cable/truss finite-element program SEADYN was used, with the problem modeled in the time-domain.

A series of time-sequenced (1 to 10 seconds, real time span) finite-element solutions to the dynamic model of the cable ship, paying out cable, were obtained. The effects of cable ship heave were neglected since the proposed operation is to take place in a Sea State of 3 or less. Depth limits representing the Escarpment bottom profile on the proposed cable route were imposed on the model, making possible the determination of cable tension at S-TD (the cable ship sheave versus distance to the point of cable touchdown), for any point along the route.

For purposes of simplifying the mathematical model, the cable was assumed to travel in a straight line from the Nanakuli South Tower to a point at the top of the escarpment. It was then assumed to be fixed at the top of the Escarpment at approximately 100 meters water depth, at a distance of 5427 ft from the South Tower at Nanakuli. The actual location of this point is Latitude: 21 deg, 22 min, 01.54 sec N; Longitude: 158 deg, 09 min, 13.42 sec W. This point is the fixed node starting location for all subsequent finite-element analyses.

It should be noted that additional information regarding details of the proposed cable route have become available in the time span between the preliminary and final versions of this report. The additional information does not affect the analysis or its conclusions; however, the detail will be summarized here for completeness:

Cable Path:

1.	South Tower	21	22	29.99	N	158	08	24.23 W
2.		21	22	34.0957	N	158	08	37.3079 W
3.		21	22	23.0011	N	158	08	49.1966 W
4.		21	22	15.8798	N	158	09	05.1523 W
5.		21	20	45.8552	N	158	11	03.3796 W
6.	Array	21	20	49.3910	N	158	11	23.1184 W

The cable element composition (Sea Cable and Shore Cable) were

varied as appropriate, and the cable elements were approximately 200 ft in length. Figure 7 shows the general configuration of the escarpment portion of the cable laying operation with typical simplex finite element cable segments.

5.2. Results of Analysis

5.2.1 Load on Sea Cable Portion of Cable

The Sea Cable extends from the rubble field at the base of the escarpment to the moored array. Typical values of sheave tensions versus ship to touchdown distance for the Sea Cable portion of the cable are shown in Figure 8. The finite element model enabled the determination of the geometry of the cable and the tensions all along the cable for any part of the model under consideration. Figure 8 shows typical results for the tower to ship distance of 25,500 ft.,, near the array termination portion of the cable, at a water depth of 3,000 ft.

5.2.2 Load on Shore Cable

Loads on the Shore Cable were analyzed in a similar manner, and all loads are summarized for all regions in Figure 9. The contour for the ship-to-touchdown distance of zero feet represents the minimum cable tension possible during the cable laying operation. For any ship-to-touchdown point distance greater than this, the sheave tensions will be higher, as shown in the figure.

It should be noted that the Shore Cable has been assumed to be 2.1 kilometers in length, and because of this, the cable will not traverse the full extent of the escarpment. It is calculated that the joint between the Shore Cable and Sea Cable portions of the cable will be located at a depth of approximately 1070 ft at an distance of 6897 ft from the Nanakuli South Tower point of reference.

5.3 Recommendations on Installation Configurations

5.3.1 Cable Laying Ship Positioning

Ship positioning is important at the start of the Nearshore portion of the operation, and at the Escarpment portion.

The Nearshore ship positioning is primarily governed by the minimum safe water depth for the prevailing environmental conditions at the time of the operation and by the type of shore termination activities anticipated. Since there is not enough information regarding either a specific cable laying ship or overall deployment scenarios, further comment about the

Nearshore startup ship positioning is not possible at this time.

It has been assumed that the initial ship-to-cable touchdown distance for the Escarpment was approximately 300 ft, with a corresponding cable tension of 2014 lb. This initial condition is equivalent to having approximately 471 ft. of cable extended from the point at the top of the escarpment.

5.3.2 Cable Laying Ship Velocity

Since one of the objects of the cable-laying operation is to minimize the residual stresses and tensions in the installed cable, it is desirable to lay the cable as near vertical as possible, in order to minimize installation tensions. This can be accomplished as shown in Figure 9 by minimizing the ship-touchdown point distance. This mode of operation implies that within areas or regions of relatively high changes in tension versus distance, the ship operates at a slower speed than in regions of relatively low changes in tension versus distance. Three distinct regions require comment.

The Nearshore region has a relatively gentle slope and correspondingly low tension versus distance rates. Therefore, this portion of the operation could have a fairly high ship velocity. However, due to the shallow water depth and the short distance from the South Tower to the top of the escarpment, it is recommended that the ship velocity be the minimum practical for the environmental conditions that prevail at the time of the operation. This minimum practical velocity is determined by the master of the cable laying vessel who will take into account the response of his vessel to varying local environmental conditions such as wind, waves, currents, and sea swell. Thus, the ship velocity for the Nearshore portion of the operation should be as low as practical while maintaining cable ship steerage-way, and the maximum ship-to-cable touchdown distance should be approximately 400 ft.

The Escarpment region has the highest tension versus distance rates, and is also the shortest of the three regions in terms of distance. Therefore, it is recommended that the ship velocity for the escarpment portion of the operation should be as low as practical, while maintaining cable ship steerage-way, and a maximum ship-to-cable touchdown distance should be approximately 400 ft.

The Downslope region has a fairly gentle slope and relatively low tension-versus-distance rates.

Therefore, for this region, the ship velocity could be as high as practical for the prevailing environmental conditions until the termination area is reached.

5.3.3 Cable Payout Rate

The payout rates are primarily functions of the bottom slope for the three regions under consideration. Using the nominal bottom slopes as a guide, the recommended payout rate for the Nearshore region is approximately 1.003 times the ship velocity. The Escarpment region should have a payout rate of approximately 1.088 times the ship velocity. The Downslope region should have a payout rate of approximately 1.008 times the ship velocity.

5.4 Recommended Maximum Tensions During Operation

Since the sheave tensions are not expected to be above 6,000 lb. for reasonable ship-to-touchdown point distances, a constant tension of 3,000 to 6,000 lb. could be dialed in, and the cable laid with this sheave tension over the entire proposed cable route. However, in the armored region of the cable, this method of cable laying would cause unnecessarily high residual stresses in the interior of the filler elements. Additionally, it would result in the cable being suspended between more points than necessary on the sea bottom, due to these higher-than-necessary cable tensions. Both of these adverse effects would reduce the service life of the installed cable.

To minimize these adverse effects, it is recommended that the sheave tension be kept as close as possible to the contours of ship-to-touchdown point distance of 0 to 400 ft, as shown in Figure 9. Therefore, it is recommended that the non-linear sheave tensions versus distance shown in Figure 9 be used as a guide in maintaining minimum possible sheave tensions. If one were to consider the three regions separately, the recommendations can be summarized as follows:

Nearshore region - The sheave tension should vary from near zero at the shore side end to approximately 2,000 lb at the top of the Escarpment.

Escarpment region - The sheave tension should vary between approximately 2,000 lb at the top of the escarpment to approximately 3,300 lb when the joint of the Sea Cable and Shore Cable is near the sheave. When the joint has passed beyond the sheave, the tension should be allowed to decrease linearly to approximately 1,000 lb, signifying that the joint is resting on the sea bottom.

Downslope region - The sheave tension should vary approximately linearly from 1,000 lb at the toe of the

escarpment to 2,200 lb near the array termination end of the route.

If cable tensions for some reason cannot be measured during deployment, then the cable payout angle should be as close to vertical as practical, always positive, and at all times less than 20 degrees from vertical.

If neither cable tension nor cable payout angle can be measured, then the cable could be deployed by noting the cable ship position and the amount of cable paid out to that point. However, this method does not consider local sea-floor and environmental anomalies that are likely to deviate from the pre-calculated nominal deployment scenario.

It is further recommended that a Precision Depth Recorder (PDR) be used to survey the bathymetry over the proposed route prior to cable laying in order to refine and/or confirm the bottom profile used in the present analysis. If needed, a refined analysis could be performed with the new information.

5.5 Summation of Recommended Deployment Methods

In order of preference, the possible deployment methods are:

5.5.1 Real-time, head-sheave tension measurement during entire deployment.

5.5.2 Real-time cable payout angle measurement.

5.5.3 Cable length payout based on a pre-calculated nominal deployment scenario.

6.0 RECOMMENDED SUBSEQUENT ACTIONS

6.1 Cable Handling

All sheaves or cable chutes used during the cable laying should maintain a cable bend radius greater than 31 in. (the lower limit of 38 in. +/- 20 percent). This bend radius would allow tensions up to 7500 lb during the deployment, without reaching yield strains in any of the cable's components. Based on the recommended cable laying scenario of Section 5.3, the tensions will be well below this level throughout the deployment.

6.2 Cable Deployment

6.2.1 It is recommended that the complete array and cable deployment procedure be set forth and reviewed with regard to the assumptions discussed in Section 5. These would include, but not be limited to: proposed cable route, assumed sea-floor profile, assumed environmental

conditions, type and size of cable-laying ship and support vessels, etc.

6.2.2 After the complete array and cable deployment procedures have been accomplished, it is recommended that a precision depth recorder (PDR) be used to survey the proposed route.

6.2.3 A refined deployment analysis should be performed to confirm the results of the present analysis when updated with information from sections 6.2.1 and 6.2.2.

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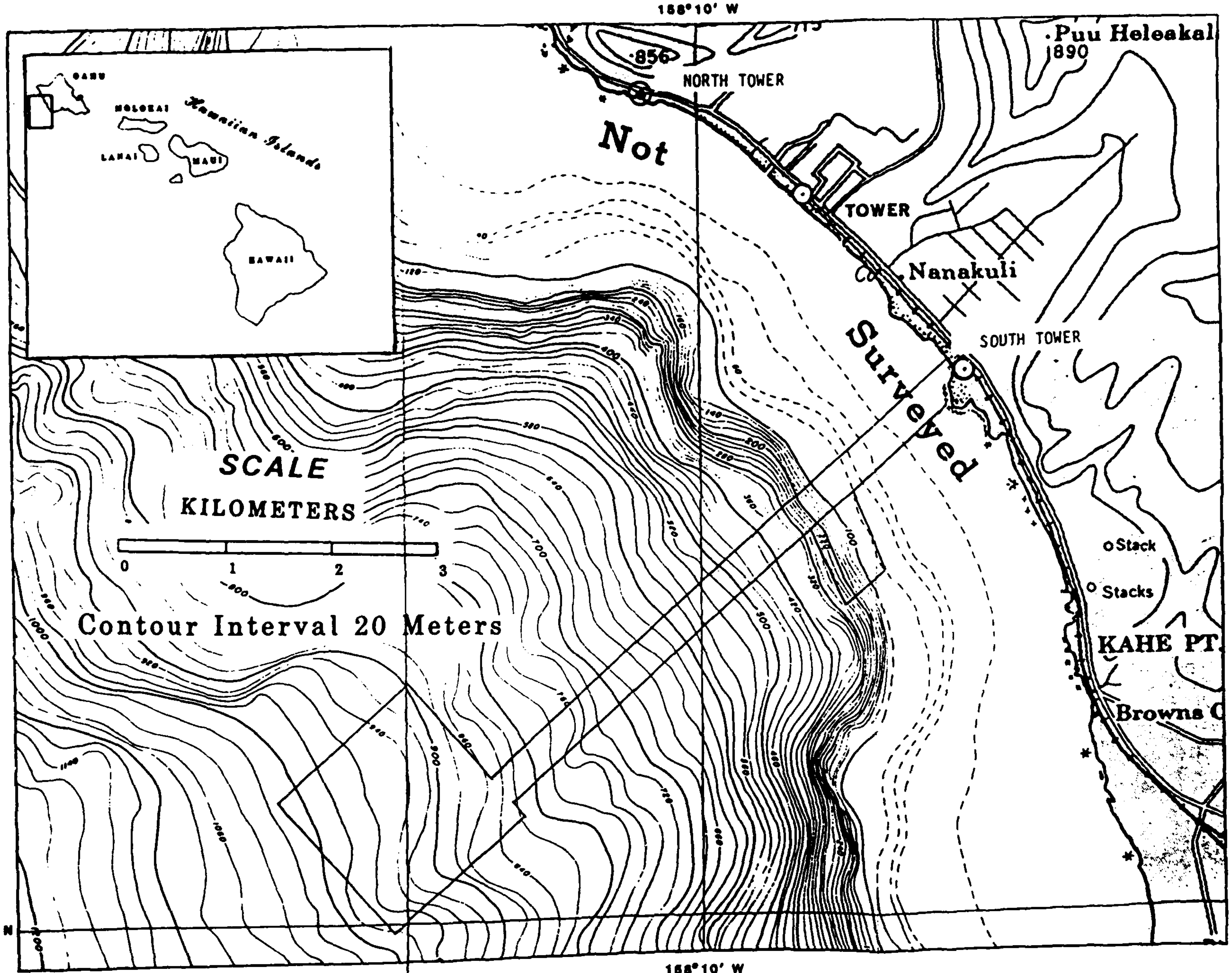

FIGURE 1: PROPOSED CABLE SITE

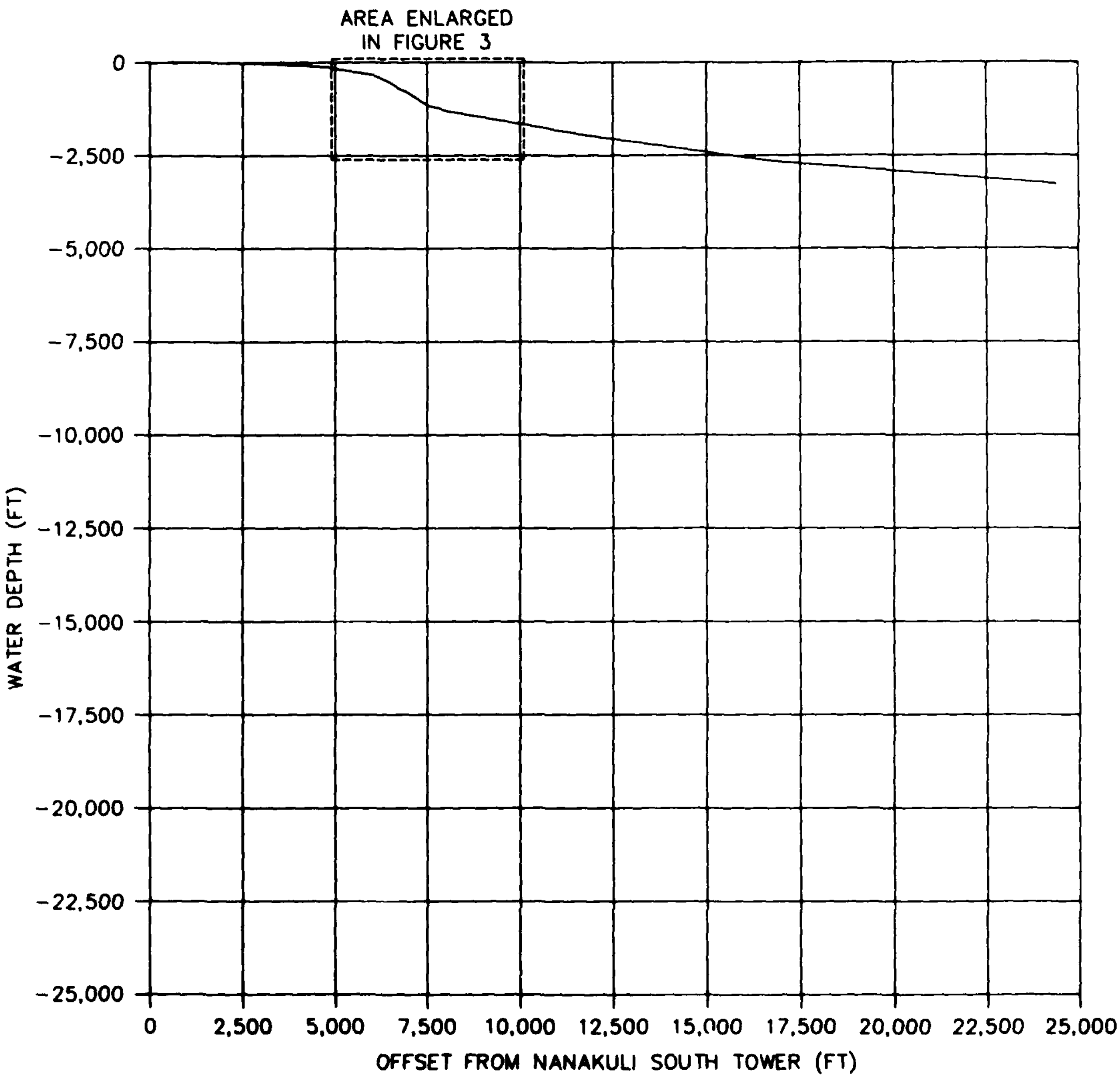

FIGURE 2: SECTION PROFILE ALONG PROPOSED CABLE ROUTE

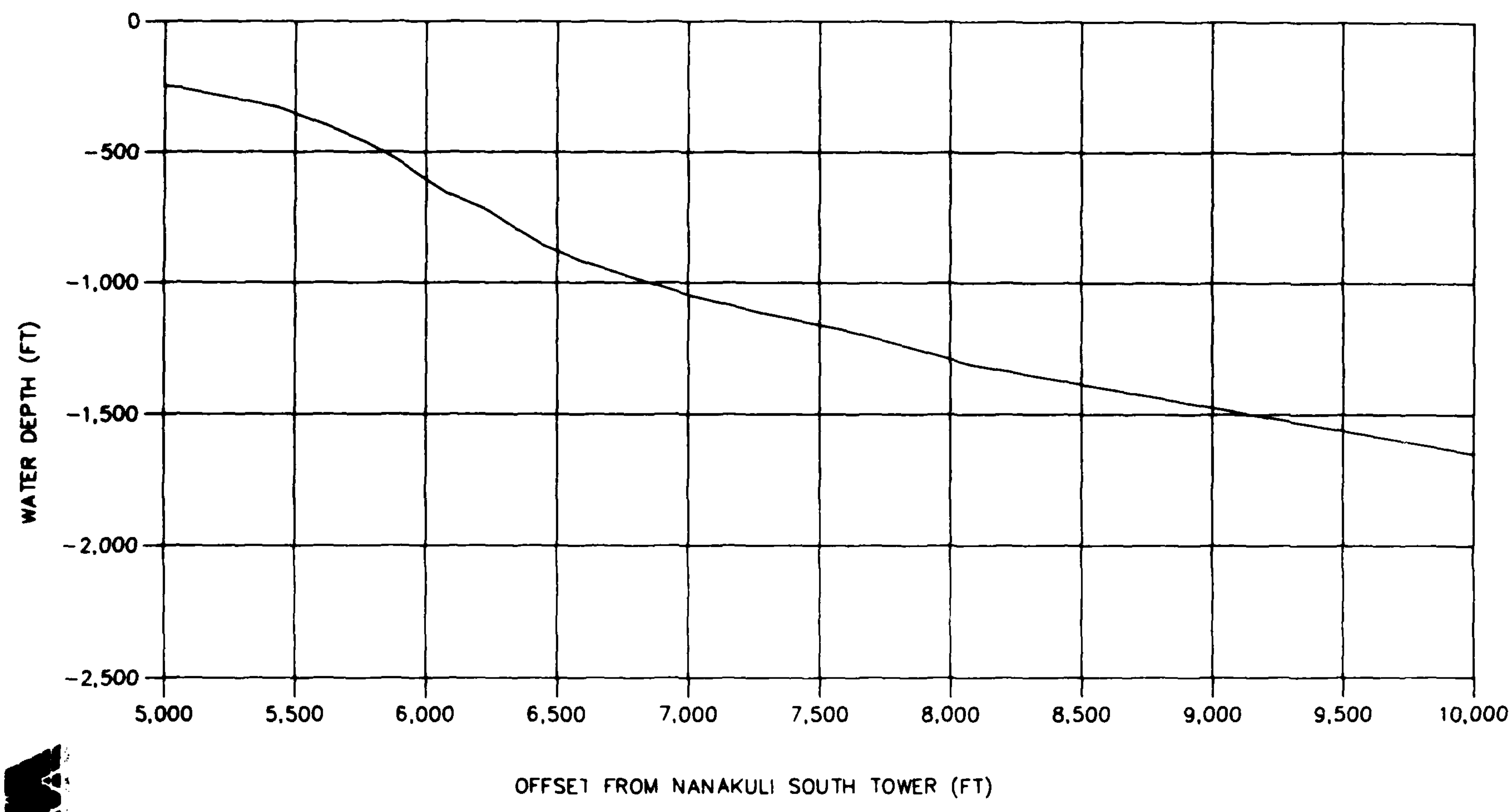

FIGURE 3: DETAIL OF PROFILE ALONG PROPOSED CABLE ROUTE

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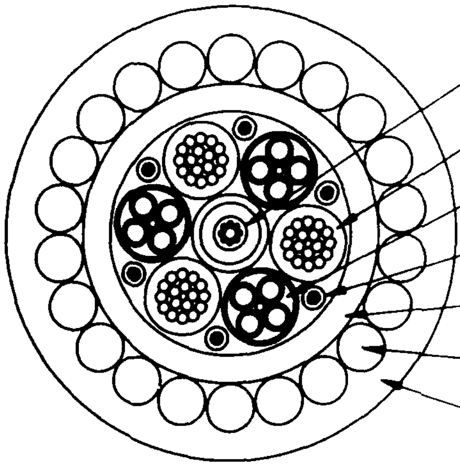
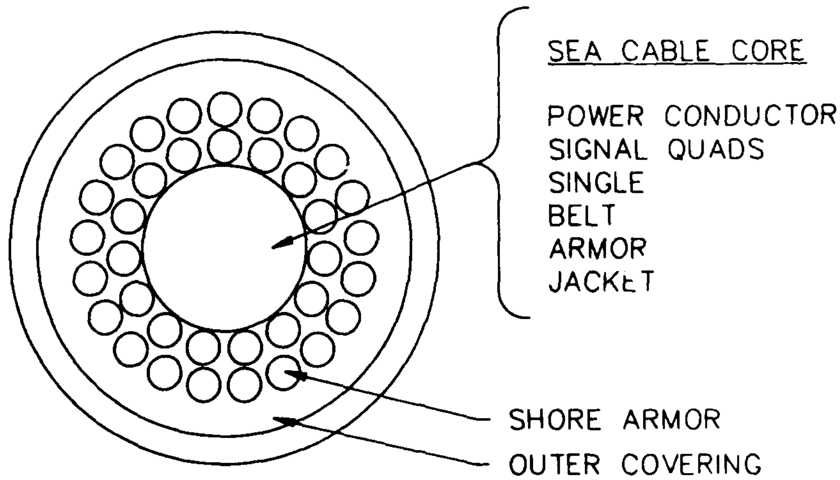


<u>FIBER OPTIC CORE (1)</u>	
8-MMF (50/125/250 μm) WITH	
JELL FILLING	.010 IN.
METALLIC BUFFER ALLOY 638	.125 IN.
HDPE BELT	.164 IN.
<u>POWER CONDUCTOR (3)</u>	
NO. 10 AWG TC MODIFIED UNILAY	
WITH COMPLIANT CORE	.115 IN.
HDPE INSULATION	.164 IN.
<u>SINGLE CONDUCTOR (6)</u>	
NO. 20 AWG TC	.034 IN.
HDPE INSULATION	.058 IN.
<u>SINGLE QUADS (3)</u>	
NO. 20 AWG TC	.034 IN.
HDPE INSULATION	.058 IN.
TWIST 4-NO. 20 AROUND	
NYLON MONOFILAMENT	.140 IN.
LDPE BELT	.146 IN.
COPPER TAPE	.158 IN.
ADHESIVE POLYESTER TAPE	.164 IN.

<u>CABLING</u>	
TWIST 3-NO. 10 AWG & 3-QUADS	
AROUND OPTIC CORE WITH	
1-NO. 20 AWG IN EACH VALLEY	.492 IN.
<u>TAPE</u>	
ADHESIVE POLYESTER	.498 IN.
<u>BELT</u>	
POLYURETHANE	.598 IN.
<u>TAPE</u>	
ADHESIVE POLYESTER	.604 IN.
<u>ARMOR</u>	
SINGLE LAYER 22 x .095 IN.	
GXIPS APPLIED AT 12° ANGLE	.790 IN.
<u>JACKET</u>	
HDPE	.900 IN.
<u>CABLE WEIGHT</u>	
IN AIR	.954 LB/FT
IN WATER	.670 LB/FT

FIGURE 4: SEA CABLE



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BELT

POLYURETHANE	.598 IN.

TAPE

ADHESIVE POLYESTER	.608 IN.

ARMOR

SINGLE LAYER 22 x .095 IN.	
GXIPS APPLIED AT 12° ANGLE	.790 IN.

JACKET

HDPE	.900 IN.

SHORE ARMOR

FIRST LAYER: 15/.203 IN.	
(NO. 6 BWG) LOW CARBON	
STEEL, 95% COVERAGE	1.306 IN.
SECOND LAYER: 21/.203 IN.	
(NO. 6 BWG) LOW CARBON	
STEEL, 95% COVERAGE	1.712 IN.

OUTER COVERING

FIRST LAYER: 40 ENDS	
JEA-100 HYTEN YARN,	
TAR SATURATED	1.914 IN.
SECOND LAYER: 42 ENDS	
JEA-100 HYTEN YARN.	
TAR SATURATED,	2.015 IN.
CHALK COATING	2.200 IN.

CABLE WEIGHT

IN AIR	5.588 LB/FT
IN WATER	4.309 LB/FT

FIGURE 5: SHORE CABLE

LOAD	SEA CABLE		SHORE CABLE	
(LBS)	AXIAL STRAIN (IN/IN)	TORQUE (IN-LB)	AXIAL STRAIN (IN/IN)	TORQUE (IN-LB)
0	0.000	0.00	0.000	0.00
5,000	0.0006	369.	0.0001	44.
10,000	0.0013	738.	0.0003	89.
15,000	0.0020	1,107.	0.0005	134.
20,000	0.0027	1,476.	0.0007	179.
25,000	0.0034	1,845.	0.0009	223.
30,000	0.0041	2,214.	0.0011	268.
35,000	0.0047	2,583.	0.0013	312.

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FIGURE 6: CSSSRNM CABLE LOADING TABLE

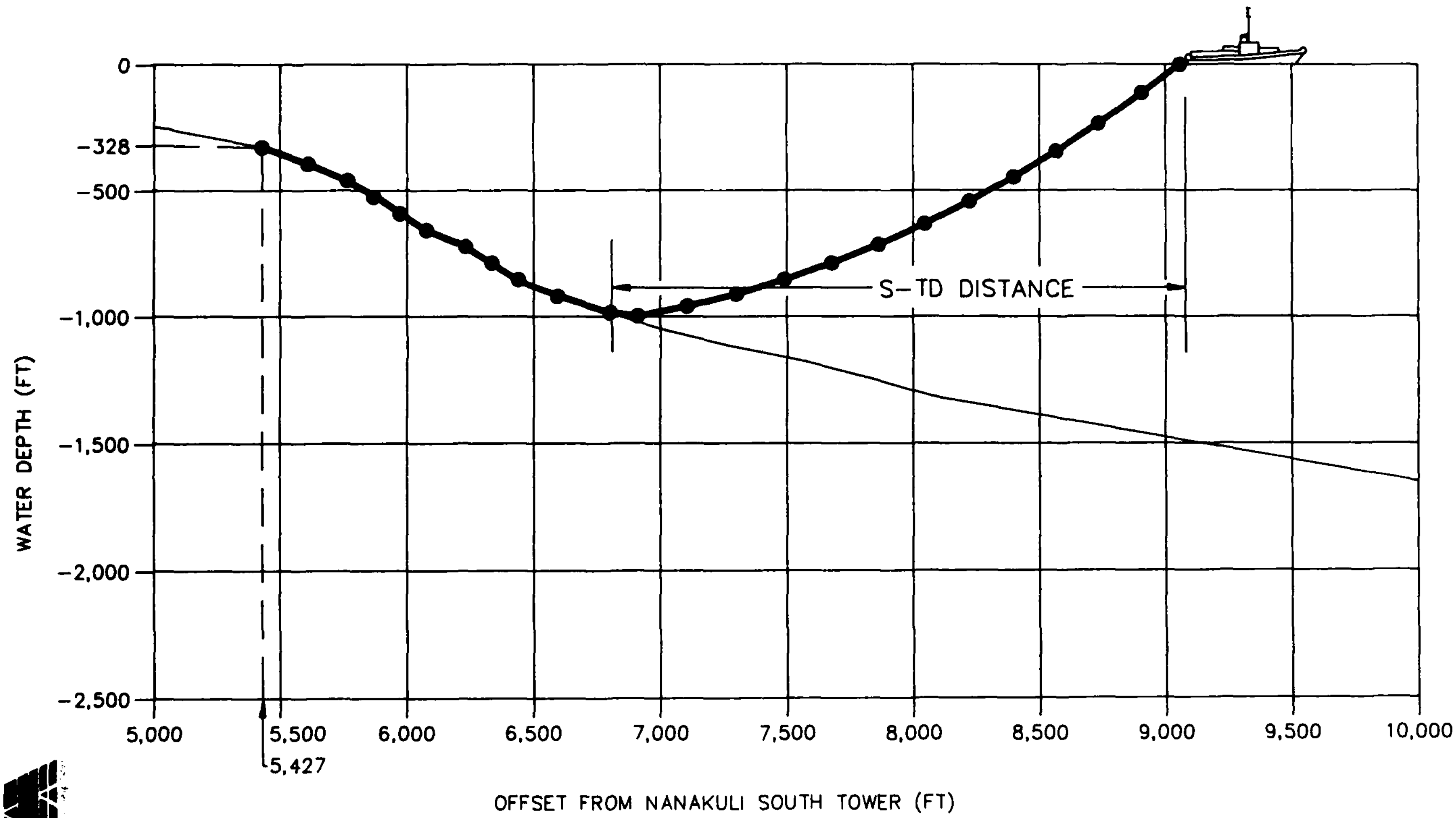

FIGURE 7: ESCARPMENT CABLE LAYING

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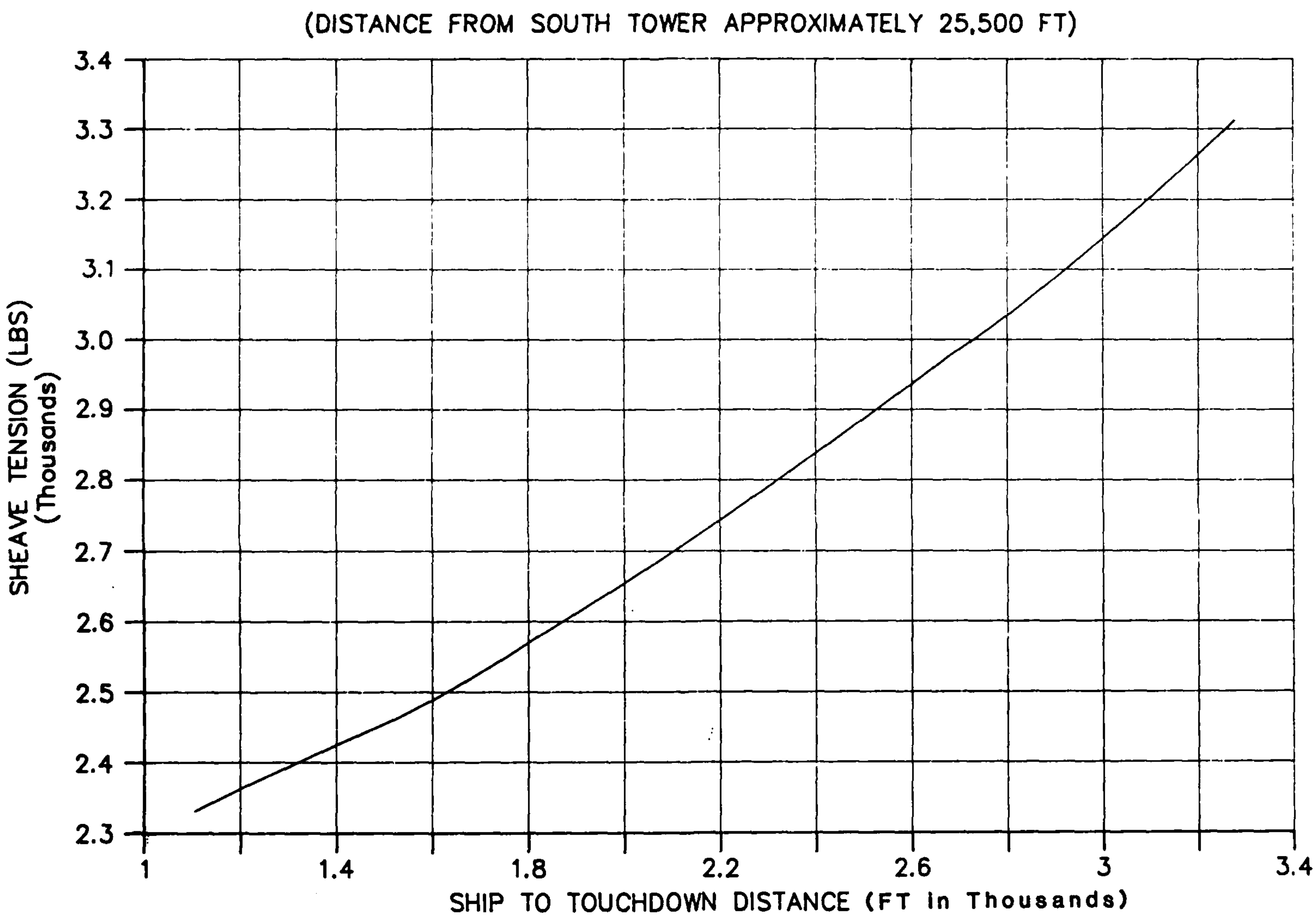
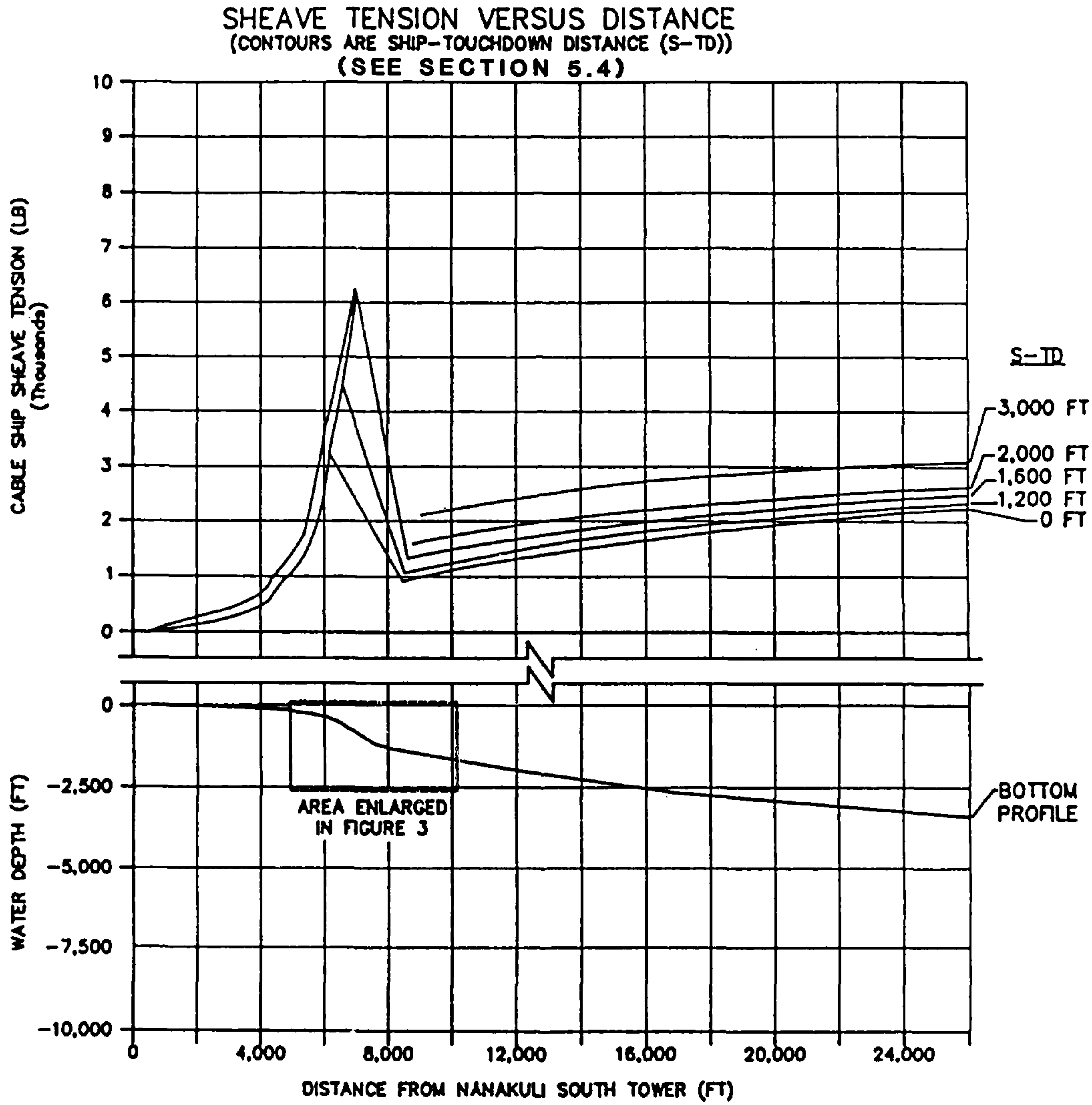


FIGURE 8: SHIP TO TOUCHDOWN VERSUS TENSION AT ARRAY



SECTION PROFILE ALONG PROPOSED CABLE ROUTE

FIGURE 9


FILM